G-Transition Induced Loss of Orientation and Reduced G Threshold

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SUMMARY

It has been suggested that the psychophysical and physiological responses to the interplay of rotation and acceleration stresses may result in spatial disorientation (SD) (18, 4). The purpose of this presentation is to review past and current evidence on the possible relationship between disorientation and acceleration stress. Accident scenarios and a number of in-flight observations will be presented together with some theoretical postulates on the mechanisms involved. Our investigation suggests that execution of a series of rapid roll manoeuvres prior to or following G transition may lead to loss of attitude awareness. This loss of attitude awareness can be attributed to perceptual confusion during roll maneuvers and the normal response of the vestibular apparatus to the rotary accelerative force acting on the semicircular canals. In addition, G threshold can also be significantly reduced immediately after prolonged rotation. This phenomenon is supported by past and current scientific evidence that the vestibular system exerts an influence on cardiovascular control. The next generation of high agility aircraft has enhanced maneuverability, which will expose pilots to a combination of translational and extraordinary angular accelerations. An understanding of the interaction between SD and acceleration stress is crucial to establish future research initiatives that will lead to appropriate countermeasures.

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INTRODUCTION

In the past 50 years, considerable progress has been made in understanding the mechanism of spatial orientation. Research on visual and vestibular inputs to orientation led to the understanding of some of the visual and vestibular causes of spatial disorientation (SD) in flight. Concerns over reactions to accelerations of high performance fighter aircraft motivated studies of the conditions that differ considerably from the range of motions that occur commonly in everyday life. For example, the perceptual responses generated by the otolith organs under sustained, higher than normal G forces were quantified. However, ground based and in-flight research on attitude perception is generally studied under the controlled change in direction and magnitude of resultant force vectors relative to the body and head. Some of the flight profiles used in these in-flight studies were dissected into single manoeuvres that typically occur in rapid sequence in flight. The two common elements that pilots are exposed to during fighter manoeuvres are rapid transition of G levels and roll maneuvers that are not possible to duplicate during ground based research. It has been reported that flying high performance fighter aircraft during offensive and defensive maneuvers regularly imposes a frequently changing force environment with multiple high G excursions (10). The frequency distributions of Gz levels during air combat maneuver in the F-18 shows that only a small proportion of each sortie was spent at moderate-to-high +Gz levels, the percentage of the sortie above +3Gz is about 7-9% (20).

Pilots frequently perform transition between high G and high roll rate in air combat. Flight path changes depend on "reorienting the lift vector". That is, the pilot maneuvers against his opponent by rapidly changing his flight path. This is accomplished by tilting or rolling the aircraft's lift vector so as to change the plane of flight. The roll rate of most aircraft decreases markedly at high Gs and at higher angles of attack. When the pilot wishes to rapidly change the direction of flight, he/she will reduce acceleration or angle of attack, roll quickly to a new attitude and rapidly re-apply acceleration to "position the nose" of the aircraft against the opponent. This is true in both offensive maneuvering, such as scissors maneuvers, and in defensive maneuvers such as the "guns jink". In other words, modern fighters are exposed to substantial linear and angular acceleration throughout the air combat manoeuvre. It has been suggested that the psychophysical and physiological responses to interplay from rotation and acceleration stress could result in SD. This paper attempts to review evidence that may support the possible relationship between disorientation and acceleration stress and begins with the description of two F-20 accidents that occurred under almost identical conditions.

F-20 ACCIDENTS INVOLVING HIGH G AND HIGH ROLL RATES

In 1984 and 1985, while practicing for air-shows, two fatal mishaps involving the F-20 occurred under very similar circumstances. The visual environments of the two accidents were also very similar with an indistinct horizon where the sky and ground lacked distinct color contrasts. The air show routine, the estimated G and the airspeed across time are shown in Table 1. Both accidents occurred near the end of the air show routine where, after a series of maneuvers involving G transitions, a 9 G pull up to the top of an "Immelman" turn, was followed by aileron rolls, and then the procedure called for a lowering of the landing gear for the final turn back to runway. Both mishaps terminated with the pilots flying the aircraft into an incorrect attitude from which they could not recover. The first one made the 9 G pull up and aileron roll and put the landing gear down but the aircraft was still inverted as the gear came down. The aircraft remained upside down for several seconds and there was an attempt to push the nose up from inverted, however the pilot could not recover and crashed. In the second accident, the F-20 made the 9 G pull up which was to be followed by a 1½ aileron roll to upright. Instead of rolling to upright, the aircraft stopped at an inverted attitude. After close scrutiny of the video of the accident, it appears that the aircraft over-banked slightly and corrected to exactly inverted when the pilot began to pull. The speed and the nose were too low to recover.

Another test pilot who had flown the identical flight profile experienced visual disruption. At about the same time frame, after the 9 G pull followed by the aileron roll, when the roll maneuver was terminated, he lost sight of the instrument panel, canopy bow and cockpit sidewalls. He reported seeing colors and saw faint brown and blue hues. However he reported that he was fully awake, alert and aware of his predicament. When his full vision returned, he was aware that he was in fact upright and the blue hue was the sky and the brown was the desert. The effects of G transition and rapid roll maneuver on the cardiovascular and spatial orientation system likely played a role in these mishaps.

EFFECTS OF G-TRANSITION

Almost 50 years ago, during an in-flight study, von Beckh reported that the effects of exposure from hypogravity to hypergravity included reduced G tolerance, G-induced Loss of Consciousness (G-LOC) at lower G values and at shorter G duration. In addition, there was a reduced efficiency in physiologic recovery mechanisms and subjects experienced higher strain (2, 3). The effects of the reverse, i.e. hypergravity to hypogravity transitions included pronounced disorientation and extended duration of G-LOC. von Beckh referred to the reduced G-tolerance and greater strain as “a logical consequence of the transition from hypogravity to hypergravity”. It was reported that the transition from hypergravity to hypogravity induced a sensation of flying in an inverted position, although no negative acceleration had been present (2). This is probably one of the early reports of the inversion illusion prior to Lieutenant B.C. Neider’s report of personal inversion while free floating during parabolic flights. Regarding disorientation related to G-transitions, von Beckh speculated that it was due to unfamiliar vestibular cues. In practice, a pilot, pulling sharply out of a dive, may experience gray-out or blackout. In order to halt the developing loss of vision, he or she may push the stick forward so that the aircraft enters a parabola. In this event the pilot may experience weightlessness, and his/her loss of sight and spatial orientation caused by the changing G’s may even be prolonged.

EFFECTS OF RAPID ROLL MANEUVER ON CARDIOVASCULAR FUNCTION

When a seated subject is rotated at constant speed about the corneoretinal axis, as defined by Hixson, Niven, and Correia (11), or more commonly known as the roll axis, blood flow along the longitudinal body axis is subjected to two force components. One is the centripetal force, $\omega^2 r$, where ω is the angular velocity and r is the radius of rotation. The other is gravity, which varies sinusoidally between +1Gz when upright and –1Gz when inverted. If the axis of rotation is below the pilot (as in high performance fighters) greater negative Gz can be experienced by the pilots. The component of the Earth’s gravitational field must be added to, or subtracted from the above according to the aircraft’s position in roll. Acceleration changes would quickly build up as a result of changes in the angle of pitch of the aircraft. However, it is the overall effect of these factors, which appears significant. Pulling +Gz, following a point-roll or unloaded barrel roll involving –Gz, can result in reduced G-tolerance as described in the preceding Section.

It has also been observed that the G threshold of some pilots is significantly reduced immediately after recovery from a prolonged rotation (14). Subjects were more liable to blackout at lower G levels than in situations where exposure to increased acceleration was not preceded by rotation. Vestibular stimulation has been shown to cause a significant decrease in blood pressure and reduction in heart rate by Spiegel (24). More recently, it was shown that high angular acceleration of the head about the yaw axis reduces the baroreflex responsiveness by 30%, suggesting that high angular rotation inhibits vagally mediated baroreflex control of heart rate and impairs orthostatically induced tachycardia (8). Recent animal studies provide convincing evidence suggesting that the vestibular system is involved in compensating for posture-related changes in blood pressure. Decerebrate cats with intact vestibular pathways (26, 27) demonstrated an increase in sympathetic nervous system output during pitch rotation, but not during roll rotation.

In humans, there is some evidence that orthostatic hypotension induced by head-down to head-up tilt in pitch orientation is more effectively compensated than head tilt in roll (5). The greater sensitivity to pitch is partially attributed to the fact that whole body rotation in roll is rarely executed.

INTERFERENCE WITH VISION DURING PROLONGED ROLL ROTATION

Modern fighter aircraft are capable of rapid rates of roll, and it has been reported that for a rapid rolling manoeuvre (≥ 200 °/s) the maximum number of continuous revolutions compatible with maintenance of a clear sense of orientation is roughly 3 to 5 depending upon type and rates of roll of the aircraft (14). During a roll maneuver the pilot is looking forward. The associated nystagmus due to vestibular and optokinetic stimuli will be about the nasooccipital axis, termed torsional nystagmus. Relatively little information is known about the dynamics of torsional eye movements induced by high-speed roll rotation in flight. It has been suggested that the rate of rotation might have been too great for compensatory eye movements to follow fixation upon the outside world or the instrumental panel when subjected to roll rates as described. Melvill Jones (15) obtained cine recordings of pitch, roll and yaw eye movements of pilots during eight-turn spins in flight. The results suggested that compensatory eye movements during the maneuver failed to stabilize the retinal image, with the greatest discrepancies in the roll plane. A laboratory study (17) upheld the conclusion that in the yaw plane optokinetic influence predominated over the vestibular-ocular reflex, whilst in the roll plane the reverse relation held and the vestibular influence was dominant. However, the optokinetic influence in the roll plane cannot be completely neglected.

More recent laboratory studies have all indicated that sinusoidal rotation of the head about the roll axis through about ± 10-15° produces little retinal slip near the fovea and so head rotation about the roll axis needs not be fully counteracted by eye movements (7, 19, 23). As in other frontal eyed animals, human torsional nystagmus should not affect visual acuity. The finding that torsional gain is lower than horizontal or vertical is partially attributed to the fact that human VOR has little experience with purely torsional head rotations, because our head rotation axes for eye-head gaze shifts normally lie within about 15° of the frontal plane.

EFFECTS OF ROLL ROTATION ON ATTITUDE PERCEPTION

Perceptually, while rolling, a pilot can become confused over the visual indicators of horizontal (12). One manifestation of visual confusion is that pilots misread the artificial horizon (22). They could become confused about whether the horizon or the aircraft symbol in the attitude indicator is locked to the gravitational vertical. Also, they can become confused about whether the entire display (and the aircraft) is erect or inverted. In flight, the resultant gravitoinertial force is aligned with the pilot’s z (spinal) axis, which could add to the confusion. During a level roll manoeuvre, the pilot retains his orientation in the aircraft cockpit but not with respect to gravity or the outside visual scene. The direction of the gravitoinertial force rotates around the pilot's head while the interior of the aircraft rotates at the same velocity with respect to the direction of gravity. If external vision is ambiguous, the only visual information available to the pilot for self-orientation is the inside of the cockpit and the visible parts of the pilot's body. If recovery is delayed, impression of the outside world could become blurred and the rate of rotation may appear to speed up. Upon recovery, when rotation is suddenly brought to a halt, an after sensation of rotation is experienced in the opposite direction and this is associated with an apparent rotation of the horizon (oculogyral illusion) and deflection of the horizon indicator. It has been reported by pilots that in practice they could neither fixate upon their instruments nor upon the visual field at the higher rates of rotation (13). Only a blurred impression of alternating dark and light was obtained.

Another effect that may lead to loss of attitude awareness during roll maneuvers stems from the short time constant in roll. The effective time constant of post-rotational decay is considerably shorter in roll which implies that a greater rate of development of error in the roll axis (16). During a period of steady rotation about any body axis the inputs from the semicircular canals cease. For rotation about a non-vertical axis, inputs from the otolith organs continue. This might have contributed to the post-roll effect – the Gillingham illusion as described by Clark and Graybiel (6) and Ercoline et al (9).

In general, there is a lack of dynamic attitude perception studies due to the difficulty in obtaining reliable information on the dynamics of spatial orientation perception on the ground and especially in the air. A large volume of perceptual data for static conditions such as sustained body tilt and perception of body tilt or tilt of a visual target are available. However, information on the dynamics of attitude perception during altered gravitoinertial environment is sparse. The effects of roll rotation in-flight on torsional nystagmus and post-rotatory judgement of self-orientation and visual orientation to gravity remain to be investigated.

CANAL RESPONSES TO RAPID ROLL ROTATION

During rotation with rapid onset rates, the cupula of the semicircular canals may be maximally deflected before the maximum stimulus is attained. In other words, the magnitude of the angular acceleration experienced is at times greater than the maximum that can be recorded by the semicircular canals. Therefore, the sensation of direction of rotation may be at times either opposite or less than that which was in fact occurring. The misleading sensation that may have been experienced is similar to that usually found when rotation is suddenly brought to a halt – the after sensation of rotation experienced in the opposite direction which is associated with the apparent rotation of the visual field.

VECTOR RELATED VERTIGO

Finally the effects of G transition and rapid rotation have also been noted in the civilian world. Civilian aerobatic pilots routinely experience both hypo- to hypergravity and hyper- to hypogravity transitions in excess of +9 to –3 Gz, as well as roll and yaw rotations at rates ranging from 20 to over 400°/s (associated with rapid onsets and sudden decreases). Over the past 10 years there has been an increasing awareness of a phenomenon of the sudden onset of vertigo, loss of balance, and extreme nausea, known as the “wobblies” among pilots (21). The phenomenon appears to occur predominantly after flight when the pilot deplanes and begin to walk. An F-16 pilot of apparent good health experienced sudden onset of severe near incapacitating vertigo following the completion of a “check-six” (looking back over the shoulder) maneuver over his left shoulder during a +7-8Gz turn (25). Upon landing, physical examination revealed that forward head tilt and rotation produced vertigo with SD predominating. A presumptive diagnosis of benign paroxysmal positional vertigo was made. It has also been documented that the dizziness experienced can be severe when pilots turn their heads, and may persist for 3 weeks or longer (1). Although the symptoms are similar to benign paroxysmal positional vertigo, the apparent etiology is unknown. The syndrome would just as well be explained by a possible mechanism involving the brain stem as it is near the main acceleration axis. In view of the next generation agile aircraft, intensive research is required to delineate this condition. In the interim, the condition is best managed clinically by recognition, and allowing time for spontaneous recovery. The likely persistence of symptoms after landing suggests that assisted exit from the aircraft is prudent and pilots should avoid repeated “insults”.

CONCLUSION

In-flight research on the conceptualization of changing orientations, directions and magnitudes of the angular and linear acceleration vectors relative to the head throughout complex motion profiles representative of aerial combat is necessary. A pilot's G tolerance may be liable to a reduction as a result of maneuvers that will provide strong vestibular stimulation that are routinely undertaken in air combat maneuvers. Further investigation in this area is warranted. Specifically, extreme pitch used in aerial combat and the repeated and very intense roll exposures accompanying them may have significant vestibular and cardiovascular consequences. The interaction of spatial disorientation and acceleration is an important issue since next generation thrust vectored superagile aircraft provide multi-axis maneuver capability. As technology progresses it is also probable that these same problems will be found in underwater maneuvering when using supercavitation principles for motion. An integrated approach to spatial disorientation and acceleration research should be developed in order to recommend the most appropriate countermeasure.

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TABLE 1. F-20 Airshow Routine

Time (min.sec)	Event	Approx Gz	Approx Speed - KCAS
0.00	Release brakes	1	0
0.15	Left climb 90° turn	1.8	155
0.23	Right aileron roll to right bank	1	200
0.27	Right 270° turn back to runway	3	200-350
0.49	Left knife-edge pass	1	375
0.56	Pull up to full Cuban 8	4	400
1.16	2 right aileron roll over top of Cuban 8	2	250
1.21	Pull up into second leg of Cuban 8	4	375-400
1.26	Right roll on “up” leg of Cuban 8	1	275-300
1.43	Inverted pass	-1	400
1.52	Right roll to upright pull to cloverleaf turn of 90°	7	425
1.56	2 left aileron rolls at top of 90° cloverleaf	1	250
2.03	270° turn back to show-line	3	250-400
2.21	1 aileron roll right, 1.5 aileron roll left to left bank	1	400-425
2.28	Level 360° turn	6	350-450
2.50	Pull up to loop	4-5G	450
3.03	2 left rolls coming over the top of the loop	0.8	250
3.19	Left 80° roll to L270° level turn	4-5G	250-450
3.36	Right Climb pull up for 120° heading change	9	450-230
3.45	1 left aileron roll	1	250-230
3.51	Left 270° turn to final	1	230-155
4.04	Touchdown	1	135